2050: 100%

Energy target 2050:

100% renewable electricity supply

Umwelt
Bundes
Amt
For our Environment

Energy target 2050:

100% renewable electricity supply

Thomas Klaus, Carla Vollmer, Kathrin Werner
Harry Lehmann, Klaus Müschen

With contribution from:
Reinhard Albert, Michael Bade, Thomas Charissé, Frauke Eckermann, Reinhard Herbener, Ute Kaulfersch, Guido Knoche, Kai Kuhnhenn, Christiane Lohse, Charlotte Loreck, Ullrich Lorenz, Benjamin Lünenbürger, Michael Memmler, Christoph Mordziol, Andreas Ostermeier, Gertrude Penn-Bressel, Anika Reetsch, Yvonne Röming, Jens Schuberth, Jan Seven, Ulrike Wachsmann, Sven Weißbach, Bärbel Westermann

In cooperation with:
Alexander Boehringer, Michael Börner, Kathrin Bruhn, Andreas Burger, Susanne Findeisen, Patrick Gniffke, Christian Herforth, Wulf Hülsmann, Kai Lipsius, Michael Marty, Werner Niederle, Diana Nissler, Ines Oehme, Peter Pichl, Sarah Rieseberg, Jörg Schneider, Sven Schneider

Federal Environment Agency

Modeling, calculation and simulation of the energy system:
Carsten Pape, Michael Sterner, Norman Gerhardt, Yves-Marie Saint-Drenan, Mareike Jentsch, Amany von Oehsen

Fraunhofer-Institut für Windenergie und Energiesystemtechnik (IWES), Kassel

Contractor of the research project „Modellierung einer 100-Prozent erneuerbaren Stromerzeugung in 2050“, FKZ 363 01 277

Dessau-Roßlau, July 2010

CONTENT

EXECUTIVE SUMMARY

In order to achieve an 80 – 90% reduction in greenhouse gas (GHG) emissions by 2050 we will first have to transform our electricity supply system. The energy sector, currently causing more than 80% of total emissions in Germany[25], has a key role to play for reducing GHG emissions. Electricity supply is responsible for about 40% of the energy sector's CO_2 emissions. The potential for reducing emissions in electricity production is very high. Given highly efficient use of electricity use and energy conversion, as well as an energy supply system that is completely based on renewable energies, GHG emissions from electricity production can be reduced to virtually zero.

For Germany an electricity supply system based completely on renewable energies by 2050 is technically as well as ecologically feasible. Such a system can be implemented using currently available production and demand side technology and without compromising neither Germany's position as a highly industrialised country nor modern behavioural and consumption patterns. This is shown in our simulation of the Regions Network scenario as well as in several studies of other institutions such as the German Advisory Council on the Environment (SRU). Aside from the Regions Network scenario, we have conceptualised two other scenarios representing extreme cases of renewable energy supply: the "International Large Scale scenario" and the "Local Energy Autarky scenario". We developed these examples of electricity supply systems to show a range of conceivable options. A real-life future energy supply system will most likely include characteristics of all three scenario types.

In our study, technical and environmental constraints were considered in the identification of the nationally available renewable energy potential. The use of biomass was strictly limited to waste and residual biomass, most of which is considered to be needed and used in the transport and industrial sectors. The electricity supply is predominantly based on wind power plants and photovoltaic.

An electricity supply system based completely on renewable energies can – at any hour of the year – provide a security of supply on par with today's high standard. The results of our simulations show that renewable energies – through the interplay of production and load management and electricity storage – can meet the demand for electricity and provide the necessary control reserve at any time. This is possible even during extreme weather events as occurred in the four-year period considered.

The expansion of reserve power capacity, application of load management and the development of infrastructure for the transport and long-term storage of electricity are necessary prerequisites for a power system based solely on renewable energies in the year 2050. To this effect, a grid expansion on a European level offers great potentials to increase efficiency.

As an important requirement for achieving a 100% renewable electricity supply, we have to tap the existing energy saving potential. This extends to more than energy use by private households. Despite the expected economic growth, the industry and trade, commerce and services sectors have to reduce their energy consumption by tapping the existing saving potential. This provided, renewable energies can cover the substantial additional electricity demand from new applications such as electric cars or heat pumps for domestic heating and hot water demand. To limit future electricity consumption for heating, very good insulation of buildings is a basic requirement.

A switch to renewable energies increases energy security. 70% of current primary energy consumption in Germany is based on the import of coal, natural gas or uranium. A complete supply of electricity from renewable energies could therefore dramatically reduce Germany's dependency on such imports and decrease its vulnerability to fluctuating or rising oil and gas prices.

A switch to an electricity supply system based on renewable energies will also be economically beneficial[26]. The costs of such a change in the energy supply are significantly lower than those of adapting to an unmitigated climate change we and future generations would have to face otherwise[27,28]. Switching to an electricity supply system based on renewable energies allows Germany to link climate protection with successful economic development, thus creating important momentum for the current international climate negotiations.

A switch to 100% renewable energies by 2050 requires decisive political support. The share of renewable electricity production has increased from 5% to 16% in the last 15 years (gross electricity production). However, there is still much work ahead if Germany wants to cover its demand for electricity in 2050 completely through renewable energies: It is not only necessary to accelerate the expansion of renewable energies but also to substantially convert the existing energy system to suit an exclusive use of renewables in the future.

It is important to define intermediate goals, particularly for the period after 2020. The earlier we start decisive actions, the more time we will have to tackle the upcoming challenges technological and societal adaptation!

FOOTNOTES:

[25] UBA 2010c

[26] SRU 2010, Enquete-Kommission 2002

[27] Stern 2007

[28] UBA 2010b

01 INTRODUCTION

In order to limit global warming to 2 degrees Celsius compared to pre-industrial levels, global greenhouse gas emissions need to be cut at least by half of 1990s levels by the middle of the century. At the same time industrialised countries must reduce their greenhouse gas emissions by 80-95 percent by 2050.

In the context of international negotiations on a new, post-2012 climate treaty, science strongly indicates that any further delay in appropriate global mitigation efforts will increase the pressure towards future mitigation measures. Industrialised countries need to lead the way in climate policy by developing and implementing strategies to decarbonise emission-intensive sectors.

Between 1990 and 2010 Germany has achieved emission reductions of 23%[1] by implementing domestic policies and measures such as feed-in tariffs and priority grid access for power from renewable energy sources (EEG), taxation of energy, insulation standards for buildings and the promotion of energy efficient technologies. In the area of electricity production from renewable sources Germany has been particularly successful, increasing the share to 16.8% of gross electricity production in 2010[2] from 3,1% in 1990.

The Integrated Energy and Climate Programme of the German Federal Government gives the right impetus to climate policy in the upcoming decade. The German Government has declared that it adheres to the target of a GHG emissions reduction of 40% by 2020 and of 80-95% by 2050. The share of power from renewable energy sources shall reach at least 35% by 2020 and 80% by 2050.

Building on a long tradition of sustainable energy scenario analysis in Germany (see e.g. Enquete-Kommission 2002), several studies have analysed pathways to reach these goals (WWF 2009, BMU 2008). A recent focus of analysis has been the feasibility of an electricity system with high shares of renewable energies (SRU 2010, BMU 2010). The reason being that the power sector is of particular importance:

Emission reduction targets of over 80% are ambitious and cannot be achieved equally well in all sectors. In the industrial and agricultural sectors reductions will be more difficult to deliver than in the energy sector. The electricity sector alone accounts for 40% of German CO_2 emissions, and without its decarbonisation overall reductions cannot be achieved. With a combination of efficient energy use and a shift to an energy system based on renewable energies, the electricity sector can be transformed into a carbonneutral system.

UBA has conceptualised three scenarios representing extreme cases of renewable energy supply: the “Regions Network scenario”, the “International Large Scale scenario” and the “Local Energy Autarky scenario”.

We developed these examples of electricity supply systems to show a range of conceivable options. A real-life future energy supply system will most likely include characteristics of all three scenario types.

In the following the three scenarios are briefly described:

- The Regions Network scenario: All regions in a country make extensive use of their regional renewables potential. Electricity is exchanged throughout the country. Electricity imports are marginal.
- Local Energy Autarky scenario: In this scenario, small-scale decentralised energy systems largely use locally available renewable energy sources to satisfy their own power demand without electricity imports. These systems make use of the maximum efficiency technologies and locally available electricity storage facilities.
- International Large Scale scenario: Electricity production and storage is based on large scale technology projects in Europe and its vicinity. Electricity is distributed via an upgraded transmission grid. Electricity production is optimised by distributing fluctuating feed-in from renewable energy most efficiently throughout Europe.

The study presented here focuses on the first option, the Regions Network scenario. The two other scenarios will be dealt with at a later stage of the project.

In the second chapter of this paper we present the framework data and modelling assumptions, energy consumption data and the potential of renewable energy in Germany. As in previous studies[3] we pay particular attention to security of supply; therefore, in the third chapter, we deal especially with load management and energy storage, presenting two storage systems which bind chemical energy either as hydrogen or methane. In the fourth chapter we present the results of the Regions Network scenario. The modelling results show that a 100% renewable energy system is technically as well as ecologically feasible. In this section we also address the question of security of supply. In the fifth chapter we formulate policy recommendations resulting from our findings.

FOOTNOTES:

[1] http://www.umweltbundesamt.de/uba-info-presse-e/2011/pe11-020_greenhouse_gases_well_below_the_limit.htm

[2] http://www.erneuerbare-energien.de/inhalt/47120/5466/

[3] UBA, (2009)

02

POTENTIALS, ASSUMPTIONS AND METHODOLOGY

The scenario presented is a 100% renewable electricity system as a snapshot of the situation in the year 2050, and it does not map out the transformation pathway. The implementation of such a system is set in the year 2050, which we believe is a realistic completion date for the restructuring of the energy system.

In our simulation, we assume that there will be no major change in today's social conditions, behaviour or consumption patterns. Germany remains a highly developed industrialised country. These assumptions are designed to illustrate how a renewable energy supply can be implemented even with current economic structures and today's lifestyle. In our simulation we deploy the best technology available on the market today. ▶

2.1 Framework Assumptions

To use a coherent data set, socio-economic model parameters were taken from the Prognos[2] reference scenario. Accordingly, Germany's population was assumed to decrease from 82.5 million in 2005 to 72.2 million in 2050.

Germany's gross domestic product (GDP) was estimated to increase to EUR_{2000} 2,981 billion, or a per capita GDP of EUR_{2000} 41.301. These parameters are indicators of the energy demand from industrial production, households as well as trade, commerce and services.

2.2 Future Energy Consumption

UBA assumes that today's best available technologies for energy-using appliances have diffused into the market and most energy efficiency potentials have been fully exploited by 2050.

Changes in user behaviour were not addressed in this study. Furthermore, we assume an increase in electrification. Due to the increase in e-mobility and electric heat pumps, electricity demand in 2050 will only be insignificantly lower than 2005 levels.

For the trade, commerce and services sector as well as the industrial sector we mostly relied on data from the Prognos reference scenario (2009), which we consider to be plausible[3].

The Reference scenario is based on today's best available technology and assumes that today's economic and industrial development will continue and today's efficiency potentials will be utilised extensively.

Final energy demand of households, the space heating requirement in industry, the demand for cooling and air conditioning in the trade, commerce and services sector as well as the electricity demand of the transport sector are based on UBA's own research and calculations. All results are shown in Table 1.

In the households, industrial as well as trade, commerce and services sectors we assume a reduction of final energy consumption by 58%, from 1639.4 TWh in 2005 to 774.2 TWh in 2050. Electricity consumption by these sectors decreases by 19%, from 492.9 TWh in 2005 to 396.7 TWh in 2050. Electricity demand experiences a lower reduction rate than final energy consumption due to the switch from fossil fuels to electricity. Total electricity consumption in our simulation is therefore 506 TWh, around 10% lower than 2005 levels (564 TWh).

Taking into consideration the wider context of a decarbonised energy sector, we as-sumed that not only the electricity, but also the heating sector must be supplied solely by renewable energy sources. Another restriction is that we also rule out the use of biomass in the heat sector (see section "Biomass"). The most important option for the supply of space heating is therefore to utilise electric heat pumps with buffer storage and solar thermal support. Beyond that, the use of geothermal heat is feasible, too, but is not quantified in this scenario.
At this stage of our report series we exclude the heat sector from further analysis and focus only on its influence on electricity consumption. The rate of building refurbishment is extremely important for reducing electricity consumption in the future space heating sector. Current refurbishment rates of around one percent per annum need to increase to 3.3 percent to realise a refurbishment of the entire existing building stock by 2050. We expect existing buildings to reduce their average space heating energy requirement from 464 kWh/m^2 to

30 kWh/m² and new constructions to consume 10 kWh/m² from 2020 onwards arriving at an average energy requirement of 26.4 kWh/m² for the entire building stock.

Although we assume that almost all energy efficiency potentials are exploited, this development is counteracted by new electric applications such as electric vehicles and heat pumps. We assume that almost 50 percent of kilometres travelled by personal cars will be electrically driven (electric vehicles or plug-in hybrids). This assumption is not a prognosis of the expansion of e-mobility but at this point we perceive it as the upper limit of a possible development. Due to these fuel shifts, electricity consumption in the transport sector increases by 50 TWh/a. We expect consumption by domestic and commercial heating and hot water appliances to amount to 44 TWh/a.

Transmission losses were estimated to amount to 30 TWh/a based on a literature review as well as UBA's own calculations.

TABLE 1 FRAMEWORK DATA: ELECTRICITY CONSUMPTION IN 2005 AND 2050

In TWh	2005	2050
Households	141	105
Of which, electric heat pumps	-	36
Trade, commerce and services sector	123	90
Industry	229	201
Transport	16	72
Of which, cars	-	**50**
Final electricity consumption	**518**	**468**
Consumption from energy conversion	16	8
Net electricity consumption	534	476
Transmission losses	29	30
Total electricity	**564**	**506**

2.3 Renewable Energy Potentials

Following the calculation of total electricity consumption, the UBA study carried out detailed research into the potential (constrained potential) for renewable electricity generation in Germany, taking into account technical and environmental constraints. The constrained potentials for the following generation types were analysed: photovoltaic, onshore wind, offshore wind, hydropower, geothermal energy and biomass.

For the calculation of the constrained potential we applied the following methodology:

For each technology the area potentially available in Germany for its deployment was determined and reduced, taking into account a) ecological considerations such as nature conservation areas, and b) competing land uses, e.g. transport routes and c) settlement area. To avoid overestimations, UBA applied ambitious constraint criteria.

After deducing the area available for energy production, the energy potential was as-sessed on the basis of weather data retrieved from a series of research institutes.

We defined the technological potential with today's best available technology. For this study we do not make any assumptions as regards the rate of innovation of renewable technologies.

In the following the application of the methodology and some results are shown for three renewable energy sources[4].

PHOTOVOLTAIC

In the case of photovoltaic energy, the constrained potential in Germany was calculated by taking into account the available space of 1620 km^2 to deploy solar panels[5] – which includes roofs and building facades – and 900 full load hours of solar radiation. Assuming photovoltaic equipment with an average efficiency of 17%, 275 GW production capacities could be installed yielding 248 TWh.

WIND POWER PLANTS

For the simulation, we assumed onshore wind power plants to have a hub height of 135 m and a nominal capacity between 1.8 and 5 MW depending on their respective location. Offshore wind power plants were assumed to be of the 5 MW category, which is commonly used today.

Excluding inter alia area under nature protection and settlement area, we arrive at the conclusion that at least 1% of Germany’s total area is suited for the construction of wind power plants. Based on this assumption we calculated an installed capacity of 60,000 MW as the constrained potential for onshore wind power. Assuming the use of very efficient installations, approximately 3,000 full load hours can be expected as an average for Germany. The potential of onshore wind energy thus amounts to 180 TWh.

Regarding the potential for offshore wind power, we refer to the “E3 scenario” of the Leitstudie 2008 (BMU 2008), which specifies an installed capacity of 45,000 MW, a figure that can be assumed to be the constrained potential. Modern offshore wind power plants achieve approximately 4,000 full load hours, which yields 180 TWh of offshore wind power.

BIOMASS

In the simulation special restrictions apply to biomass. Energy crops cause a series of problems: a significant carbon footprint, competition with food and fodder production, destructive land-use change as well as increased negative environmental impacts of agricultural production on soil, water and biodiversity. Due to the critical nature of bioenergy, the UBA study rules out the use of energy crops or imported biomass for electricity or heat production and instead limits the type of biomass that would be used for this purpose to nationally available organic wastes and residues.

In our study even waste and residual biomass was assumed to be used in electricity production to a very limited degree, because its use as raw material in the chemical industry or as an alternative energy source in the transport sector is of paramount importance.

Biomass would be utilised to fuel gas turbines which serve either as reserve or as peak-load power plants, but only if there is additional power demand after the optimised utilisation of load management and pump storage power plants.

TABLE 2 RATE OF UTILISATION OF AVAILABLE RENEWABLE ENERGY POTENTIAL IN GERMANY

	CONSTRAINED POTENTIAL*		REGIONS NETWORK SCENARIO*		
	CAPACITY IN GW	ELECTRICITY GENERATION IN TWH	CAPACITY IN GW	ELECTRICITY GENERATION IN TWH**	RATE OF UTILISATION IN %
Onshore wind	60	180	50	170	100
Offshore wind	45	180	45	177	100
Photovoltaic	275	240	120	104	44
Hydropower	5.2	24	5.2	22	100
Geothermal	6.4	50	6.4	50	100
Biomethane from waste and residues[6]	Depending on system requirements	23	23.3	11	48

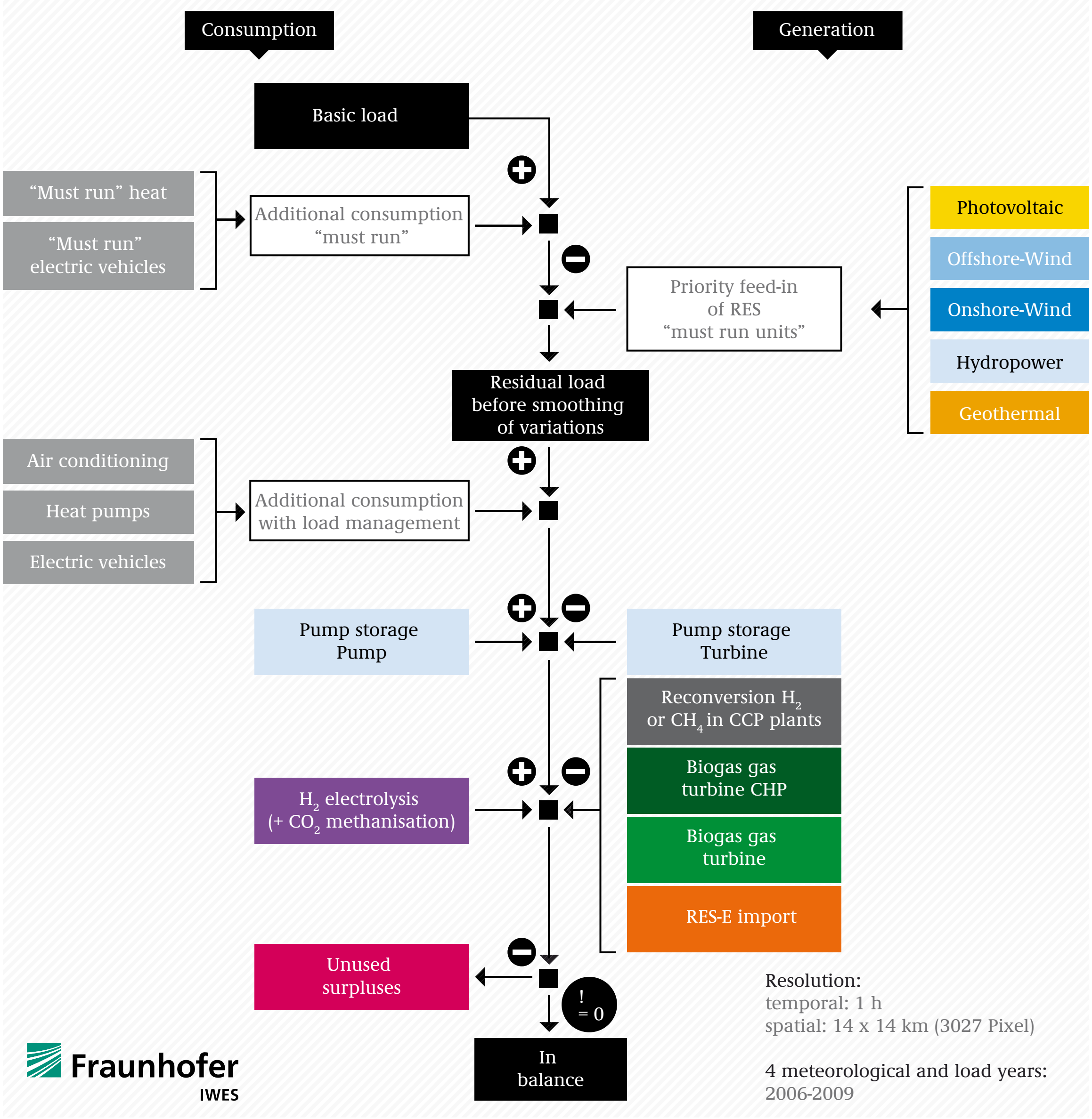
*All figures refer to net generation **Average of four meteorological years

2.4 The SimEE Energy System Model

The simulation of the Regions Network scenario was conducted by the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) on behalf of UBA using the SimEE model[7]. The model (Figure 1) simulates electricity production from installed renewable energy capacities and storage facilities, the load curve and selected load management options over several years. The simulation is carried out in hourly resolution and chronological order. Wind and photovoltaic energy production and the use of electric heat pumps can be simulated in a spatial resolution of 14x14 km[8]. The dynamic simulation of renewable feed-in and load in 2050 is based on meteorological data and load characteristics from four example years, 2006-2009. Since the simulation covers several years and therefore allows different weather extremes to be taken into account, more general conclusions can be drawn.

In a first step the load is covered as far as possible by feed-in from wind, photovoltaic, hydropower and geothermal energy. Electricity production from these sources is determined on the basis of weather data, considering availability of production capacities, their spatial distribution and assuming the use today's best available technology.

FIGURE 1 STRUCTURE OF THE SIMEE MODEL



Resolution:
temporal: 1 h
spatial: 14 x 14 km (3027 Pixel)

4 meteorological and load years:
2006-2009

© FhG IWES

The load amount was calculated based on population, energy efficiency and "new-application assumptions" for 2050. The study cannot make predictions about altered patterns in the use of electricity technologies. We defined a "basic load curve", which covers all current types of electricity consumers, excluding the "new electricity applica-tions". This curve is based on historical load data from the European Network of Transmission System Operators for Electricity.

So called "new" electricity uses comprise the large increase in e-mobility and in the use of heat pumps, and additional air-conditioning. They were simulated in conjunction with load management. In a second step of the simulation, load management was applied to reduce the residual load, which is the difference between load and feed-in from all renewables - except for biomass. Where feed-in proves to be insufficient to cover the load, in a last step stored energy (pump storage and chemical storage systems), biomass-fired reserve power plants and imports are utilised. Surplus energy is stored in large part either in short-term storage facilities (pump storage) or in long-term chemical storage systems (hydrogen or methane) to be reconverted at a later point.

As part of the simulation a comparison was carried out between rp-hydrogen and rp-methane storage. These simulation included assumptions on the storage efficiency of pump storage power plants, losses during electrolysis, compression, transport and reconversion for the hydrogen- or methane-based storage systems and additionally losses from the Sabatier process in the case of methane-based storage. Particular attention was paid to security of supply and the availability of sufficient balancing power for a stable grid. In the simulation we assumed that in 2050 transmission grids will have been sufficiently upgraded and the current problem of lacking grid infrastructure for renewable electricity distribution would no longer be an issue; Germany therefore was simulated as a coherent "copper plate", the balancing of feed-in and load taking place in a single national control area.

FOOTNOTES:

2 In WWF, 2009

3 Some studies present similar efficiency results for the year 2050: BMU 2009a, Greenpeace 2009, UBA 2002; whilst others do not: FFE 2009c

4 For further information see UBA 2010

5 DLR/FEU/WI 2004

6 Only includes the fraction of biomass from waste and residues that is suitable for the production of biogas, which in turn can be used in modern combined cycle gas turbines with an electric efficiency of about 56%

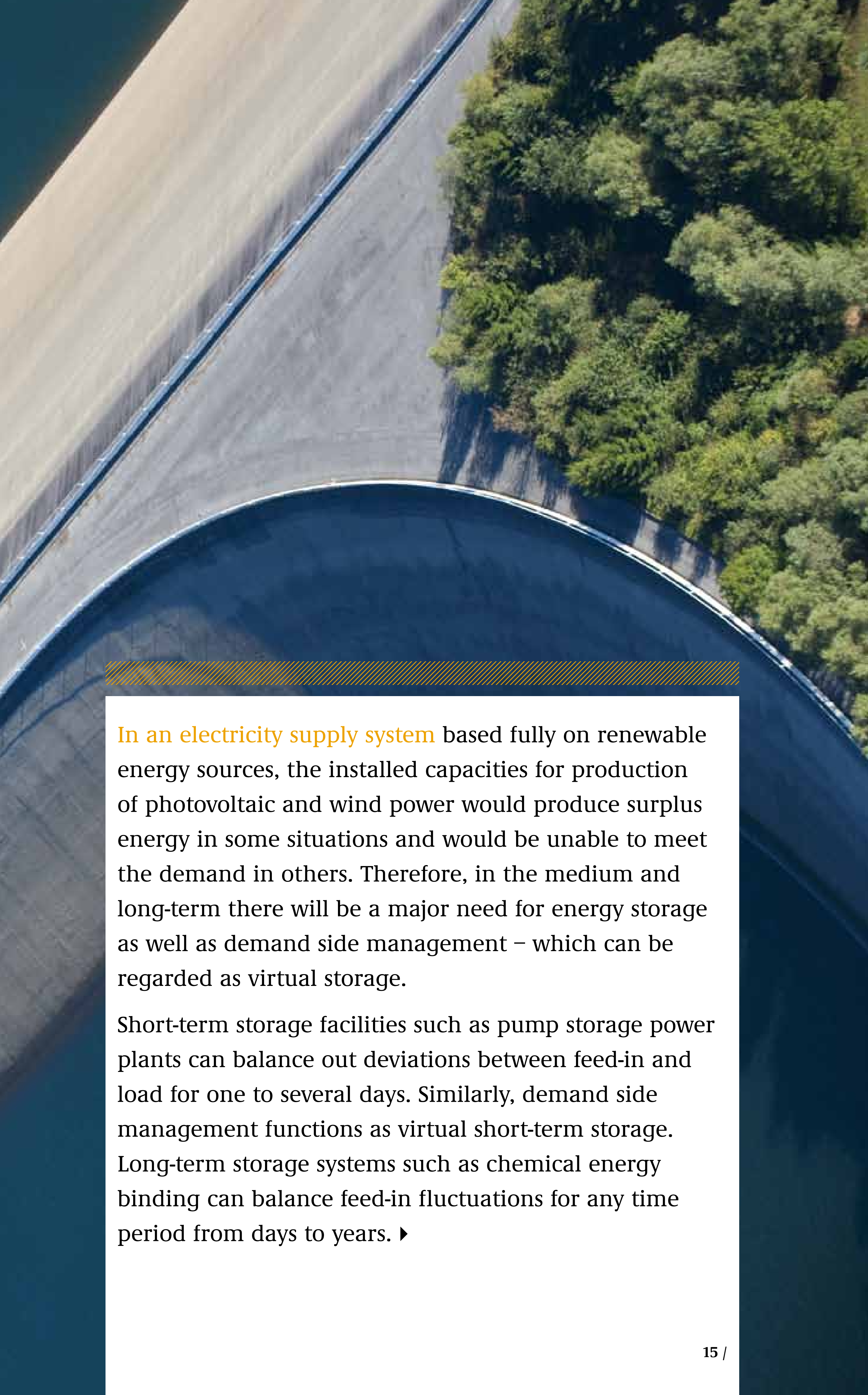
7 Saint-Drenan et al. 2009; Sterner et al. 2010

8 This resolution corresponds to a grid of 3,027 planning areas onshore and 598 planning areas offshore, each 14 x14 km in size.

2050:
100 %
RENEWABLE ELECTRICITY

03

ELECTRICITY STORAGE AND LOAD MANAGEMENT



In an electricity supply system based fully on renewable energy sources, the installed capacities for production of photovoltaic and wind power would produce surplus energy in some situations and would be unable to meet the demand in others. Therefore, in the medium and long-term there will be a major need for energy storage as well as demand side management – which can be regarded as virtual storage.

Short-term storage facilities such as pump storage power plants can balance out deviations between feed-in and load for one to several days. Similarly, demand side management functions as virtual short-term storage. Long-term storage systems such as chemical energy binding can balance feed-in fluctuations for any time period from days to years. ▸

3.1 Pump Storage Power Plants

Since our study is based on technologies available on the market today, we restricted the options for short-term storage to pump storage power plants[9]. Pump storage plants store the gravitational potential energy of water. These plants are deployed around the globe. Modern pump storage plants achieve storage efficiencies of more than 80% and can also provide positive and negative balancing power as well as reactive power.

The installed net capacity in Germany is 6.6 GW[10], the total storage capacity comprises about 40 GWh[11]. Applying a conservative approach and technical and environmental constraint criteria, we assumed an expansion by 2050 to an installed net capacity of 8.6 GW and a total storage capacity of 60 GWh. In the simulation, pump storage power plants provide 4 GW primary and secondary reserve power as well as 4.6 GW turbine capacity and 3.9 GW storage capacity for regular schedule operation.

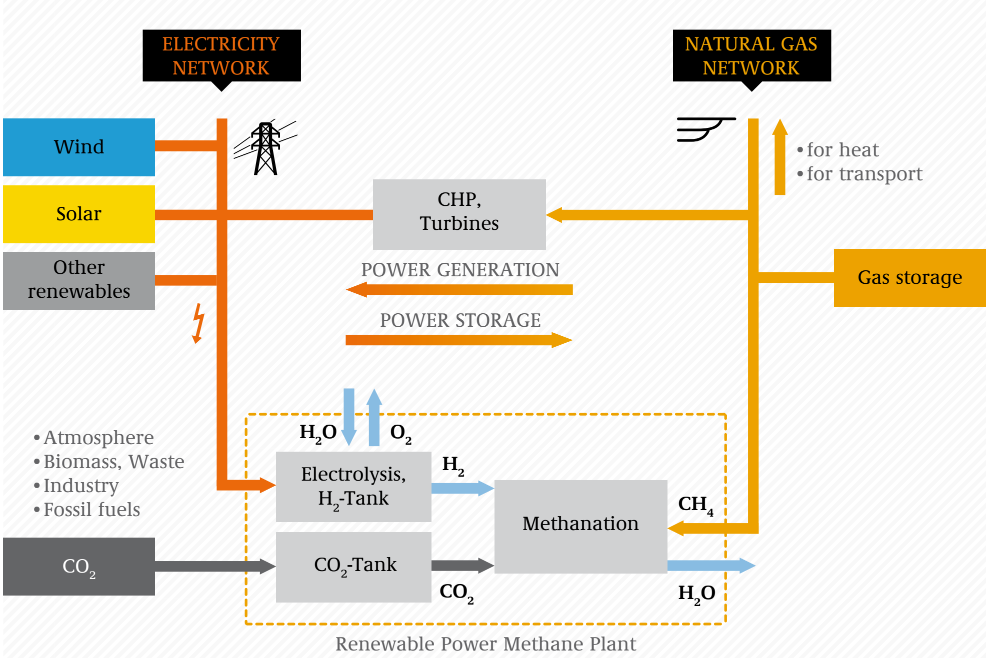
3.2 Chemical energy binding

Electricity can also be converted into chemical energy and stored in this form for long periods and transported. This is achieved e.g. by converting electricity into hydrogen via electrolysis. Ideally, the chemical reaction takes place close to the location of electricity production to reduce electricity transmission infrastructure requirements. In a further reaction it is possible to convert hydrogen into methane by means of the Sabatier process.

The infrastructure already in place for natural gas allows for an efficient distribution and storage of rp-methane. In contrast, rp-hydrogen would require an additional transport grid but offers higher power-to-power storage efficiencies.

Both gases can be stored in underground spaces, so called cavern and pore storage facilities. As required, the chemically bound energy can be reconverted into electricity or used for other purposes (Figure 2).

FIGURE 2 CONCEPT FOR THE TRANSFORMATION OF EXCESS ELECTRICITY FROM RES VIA HYDROGEN TO METHANE (SNG) WITH RECONVERSION IN COMBINED HEAT AND POWER PLANTS GAS TURBINES OR COMBINED CYCLE POWER PLANTS[12]



To achieve high efficiencies reconversion should take place in fast-response CCP plants close to the centres of electricity consumption. Currently CCP plants achieve net efficiencies of 59%.

Chemical storage allows for innovative load and generation management. Storage limits the need for additional production capacities and reduces stress on the transmission grid, e.g. when rp-methane is transported through the existing natural gas grid instead. Therefore much of the electricity from renewable energy sources which otherwise could not be absorbed by the grid can be utilised[13].

Beyond that rp-methane and rp-hydrogen can be used in the chemical industry or as alternatives to fossil fuels in the transport sector.

RP-HYDROGEN STORAGE SYSTEM

Rp-hydrogen derived from electrolysis can directly function as energy carrier. The direct use of hydrogen is more efficient from an energy perspective as no additional losses for the conversion into methane occur. The electric system efficiency of an rp-hydrogen storage system is about 42%.

Electrolysers, particularly pressure electrolysers, are fast-response capacities in the load management portfolio. They respond to load changes almost without any delays and can be started up or shut down within less than 15 minutes[14]. In addition to the use of surplus energy, electrolysis is excellently suited to react to feed-in fluctuations from intermittent energy sources such as wind and photovoltaic and to provide balancing power. It can thus make a major contribution to guaranteeing stable grid operation.

Pressure alkaline electrolysers have been employed on a commercial scale for years to produce hydrogen for the chemical industry. Already today, several demonstration projects with a capacity of up to 1 MW achieve efficiencies of up to 82% (based on the heating value) at their optimum operating point[15].

Industrial companies have operated pipelines for the transport of highly compressed gaseous hydrogen in several regions for quite some time. In contrast to an rp-methane system, an rp-hydrogen system requires the construction of additional transport infrastructure. A long-distance transport network with few connection points would, however, be sufficient.

As methane, hydrogen can be used in gas turbines as well as in CCP plants. Gas turbine power plants running with pure hydrogen are not yet available on the market. However, special gas turbines are already capable of generating electricity based on electrolytically produced hydrogen, if the hydrogen is diluted to a content of 60-70% by mixing it with nitrogen or CO_2[16]. These turbines are already available on the market but lack longstanding practical experience.

RP-METHANE STORAGE SYSTEM

The methane storage system requires an additional conversion process from hy-drogen to methane. Conversion losses are therefore higher, but on the other hand the existing natural gas infrastructure can be utilised.

In the case of the synthesis of methane we deviate from our original premise of relying solely on currently available technologies. The Sabatier process has not played a role in energy production to date, but its technical feasibility was demonstrated in pilot plants.

Methane synthesis has an efficiency of 75-85%[17],[18]. The electric system efficiency of the rp-methane storage system is around 35%.

TABLE 3 COMPARISON OF EFFICIENCIES OF CHEMICAL ENERGY BINDING SYSTEMS

	HYDROGEN STORAGE SYSTEM	METHAN STORAGE SYSTEM
Electrolysis (full and partial load)	74-82 %	
Methanation*	-	83 %
Storage, including compression and transport*	93 %	
Reconversion*	57 %	57 %
Total system efficiency**	42 %	35%

*Average efficiency **results of the simulation

STORAGE CAPACITIES

In the future, large quantities of rp-methane could be stored in underground pore storage spaces, such as depleted gas and oil fields and aquifers[19], or in salt cavern[20], just like natural gas is stored today. Hydrogen storage in salt caverns is particularly suitable, and is already the state of the art today. The constrained potential of storage capacities in Germany is equally sufficient for rp-methane as for rp-hydrogen[21].

3.3 Load Management

Load management allows suitable electricity applications to be retimed or shut down to minimise load peaks in those situations when load considerably exceeds feed-in from RES. Demand is shifted to those times when feed-in from renewable sources exceeds the load.

Suitable for load management are all those applications whose energy demand is dispatchable because they are either equipped with electricity or heat storage or can be dispensed with temporarily (e.g. charging the battery of a plug-in-hybrid vehicle).

The prerequisite to load management is the application of modern information and communication technology. Generally, one can divide applications suitable for load management into two groups

a) Consumers with high loads, e.g. production of steel. Due to economic considerations production processes can only be shifted for a certain time.
b) Consumers with lower loads but more flexibility for temporary shifting, e.g. cooling or heating applications or e-mobility

In addition to hydrogen electrolysis as described above, electric heat pumps, airconditioning, e-vehicles and large industrial consumers offer the largest potential for load management.

These potentials - with the exception of those in industry - were incorporated in the simulation (see Table 4). Further potentials in the area of domestic applications were not considered but constitute an additional potential reserve.

TABLE 4 MODEL INPUT: BASIC LOAD AND DISPATCHABLE LOADS IN TWh/a

APPLIANCES IN	AVERAGE ELECTRICITY CONSUMPTION	LOAD MANAGEMENT
Electric heat pumps*	44	44
Electric vehicles	50	40
Cooling in trade, commerce and services sector*	28	10
Total electricity demand	506	94

*Average efficiency

FOOTNOTES:

9 Adiabatic Compressed Air Energy Storage (ACAES) power plants, which are CAES plants without a loss of temperature of the pressurized air, are still under development.

10 DENA 2008a; WWF 2009

11 Kleimaier 2010; Schulz 2009

12 Sterner 2009

13 ZSW/IWES/Solar Fuel 2009

14 Brinner 2002

15 FVS 2004

16 According to gas turbine manufacturer „GE“, gas turbines and CCP plants are available on the market which can use gas mixtures composed mainly of hydrogen and a small share of inert gases. These gas turbines are designed, in particular, for use in IGCC plants, i.e. plants for gasification of carbon-containing compounds, with carbon capture (CCS) and subsequent use of the hydrogen-rich fuel gases for electricity generation (GE 2009).

17 Sterner 2009

18 A pilot plant developed by the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) reaches an efficiency of around 82%. Considering upscaling 85% are probably achievable. (Sterner 2010)

19 Aquifers are water-bearing rock strata.

20 Salt caverns are artifically hollowed spaces in geological salt formations.

21 Until 2050, around 36.8 billion m^3 (V_n) hydrogen or methane can be stored in caverns alone.

2050:
100 %
RENEWABLE ELECTRICITY

04

REGIONS NETWORK SCENARIO: RESULTS OF THE SIMULATION

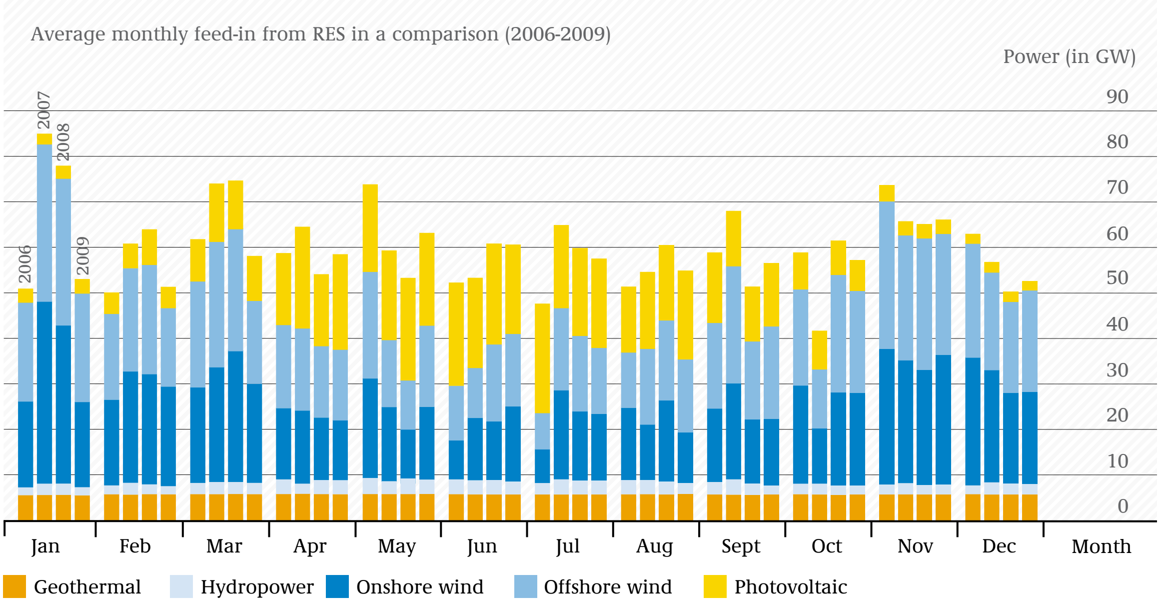
4.1 Feed-in from Renewable Energy Sources

In the simulation the installed renewable-energy generation capacities amount to 260 GW, though at no point in time the entire fleet generates power simultaneously.

Figure 3 shows the feed-in in the four example years. The highest monthly average is in January 2007 at approximately 85 GW. The lowest monthly average is observed in October 2007 at 40 GW. Noteworthy are the windy winter months and sunny summer months as well as the fact that the monthly wind-power feed-in (blue) and photovoltaic feed-in (yellow) complement each other very well.

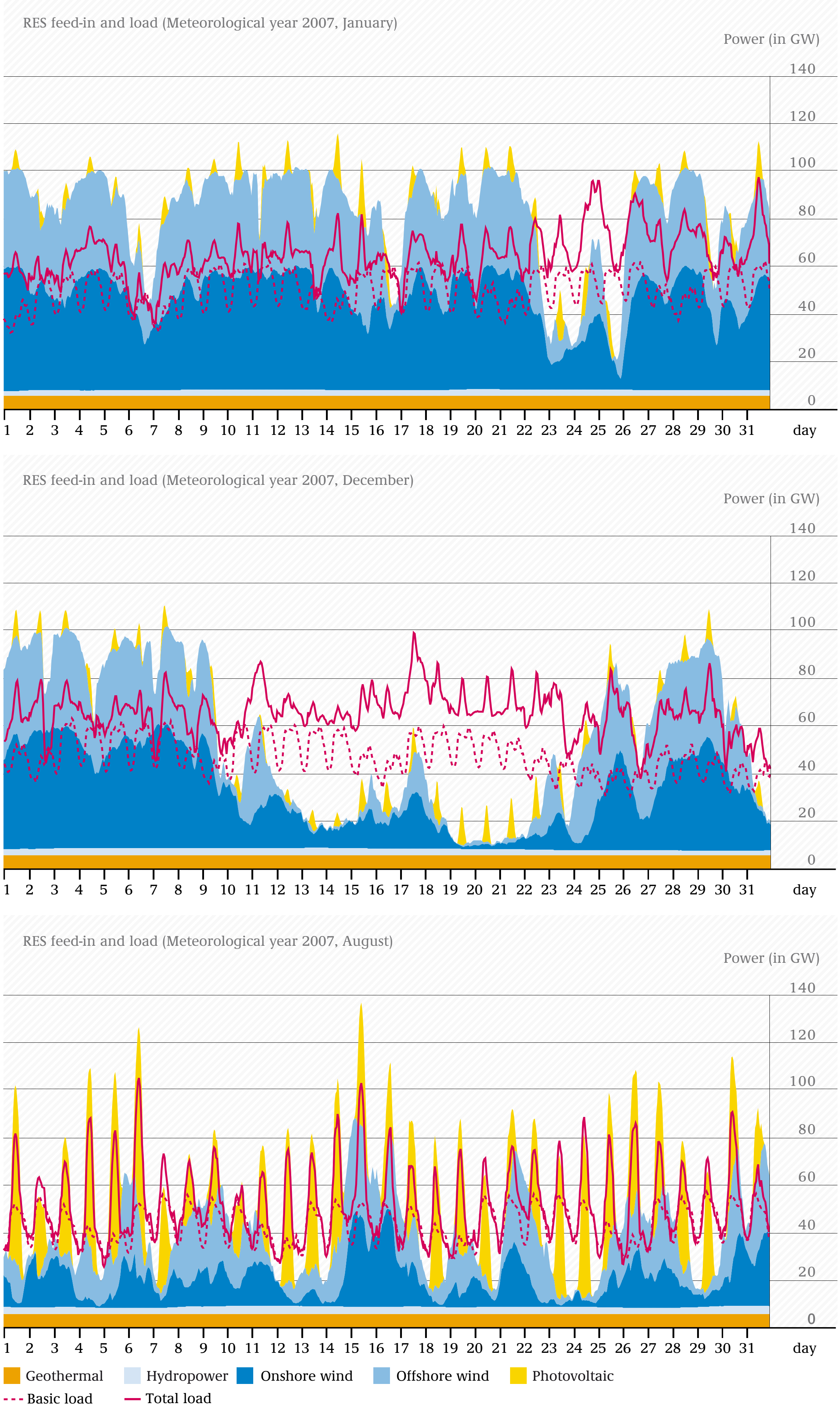
Due to the variability of weather conditions, feed-in from renewables may vary greatly over an hour, but this can be compensated to some degree by adjusting the load through load management. Figure 4 shows the months January and December 2007 as examples to illustrate this. The continuous red line shows the total load (defined as basic load + heat pumps + e-vehicles + air conditioning). It can be seen that in January the load can largely be covered by renewable energy. In contrast, December was a rather unproductive feed-in month. Due to a two-week period with little wind, renewable generation could not have satisfied the load demand without falling back on stored energy for considerable periods of time. The bottom figure exemplifies a summer month – August 2007. Noticeable load spikes occur simultaneously with maximum feed-in from photovoltaics. The correlation is a result of load management.

FIGURE 3 MONTHLY FEED-IN FROM ALL RENEWABLE ENERGY SOURCES IN THE YEAR 2050 BASED ON THE METEOROLOGICAL YEARS 2006-2009 (MONTHLY AVERAGES).



© FhG IWES

FIGURE 4 EXAMPLES OF FEED-IN FROM RENEWABLE ENERGY SOURCES IN THE YEAR 2050, BASED ON THE METEOROLOGICAL YEAR 2007: JANUARY (TOP), DECEMBER (CENTRE), AUGUST (BOTTOM)



RES feed-in and load (Meteorological year 2007, January)

RES feed-in and load (Meteorological year 2007, December)

RES feed-in and load (Meteorological year 2007, August)

© FhG IWES

4.2 Residual load

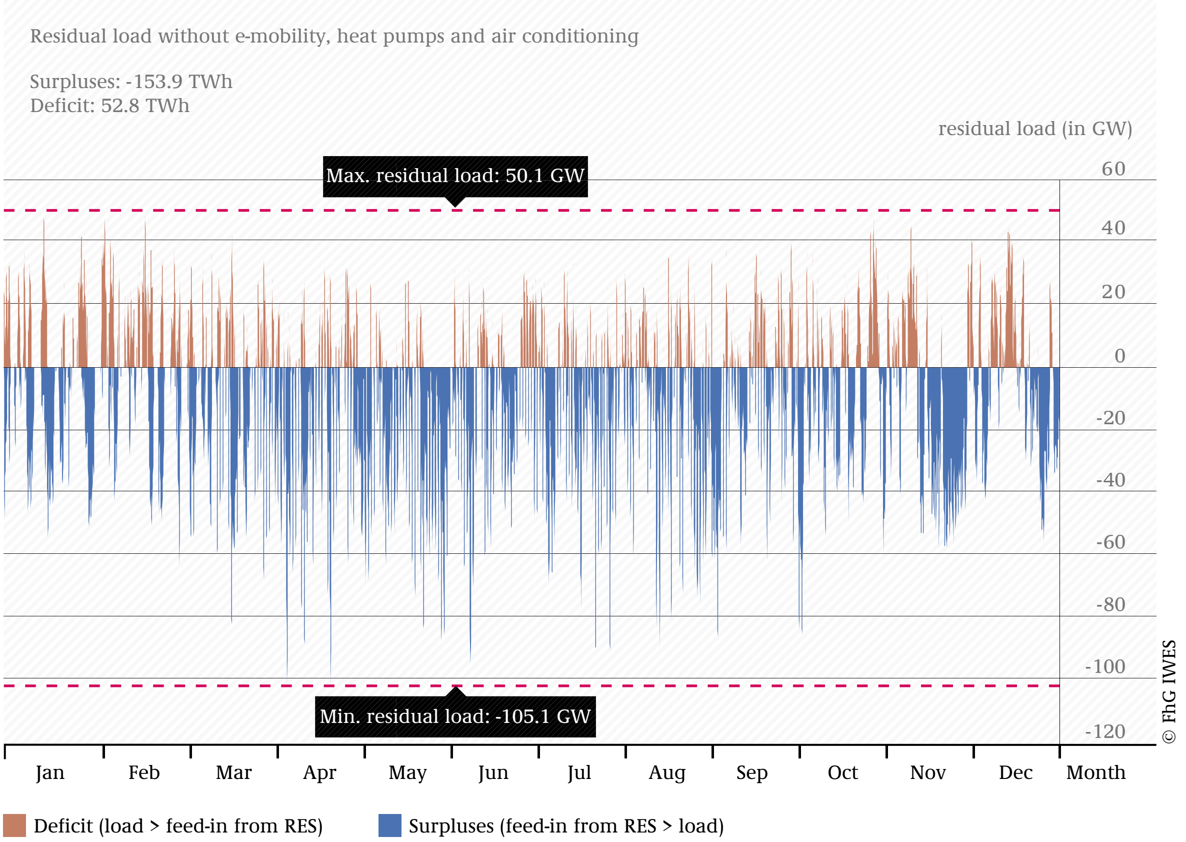
The residual load is the remaining load which is not directly covered by feed-in from renewable energy and is obtained by subtracting renewable generation from the load. Positive values signify that the remaining load needs to be covered by storage and reserve capacities or by imports. Negative values indicate an excess supply of energy.

RESIDUAL BASIC LOAD

The residual basic load is shown in Figure 5 for the meteorological year 2009. It is calculated as the difference between basic load and generation of renewable energy (without biomass).

As evident from the above figures, renewables cannot at all times cover the basic load without the use of storage (red areas of Figure 5). At the same time, it can be seen that in the course of the year there are several points in time at which feed-in from renewables exceeds the current basic load and excess power is available (blue areas). Excess supply spikes (up to -100 GW) occur more frequently and are more pronounced than deficit spikes (up to +50 GW). With the excess supply, deficits can be offset, on condition that the excess energy can be stored.

FIGURE 5 RESIDUAL BASIC LOAD FOR 2050, BASED ON DATA FROM THE METEOROLOGICAL YEAR 2009

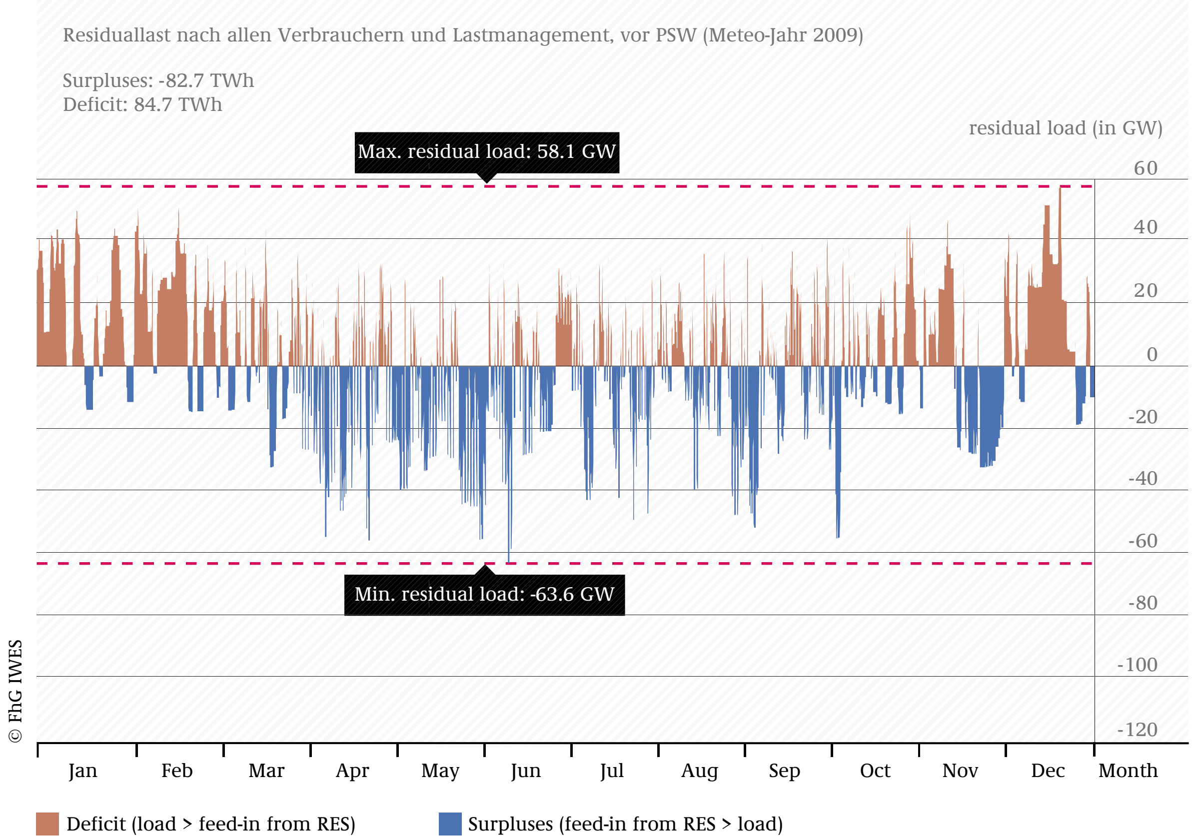


TOTAL RESIDUAL LOAD

Total residual load is calculated as the difference between total load, which is defined as basic load plus demand for air-conditioning, e-mobility and heat pumps including load management, and generation from renewables (excluding biomass).

Unlike the residual basic load, the total residual load reflects the effects of load man-agement, as shown in Figure 6 for the example year 2009. By re-timing both, the charging of e-vehicles and the use of air-conditioning and heat pumps, the excess supplies can be skimmed to some extent. The additional consumers increase load spikes, despite load management, though considerably less than in the case of uncontrolled demand.

FIGURE 6 TOTAL RESIDUAL LOAD WITH LOAD MANAGEMENT (WITHOUT PUMP STORAGE) IN THE YEAR 2050, BASED ON DATA FROM THE METEOROLOGICAL YEAR 2009



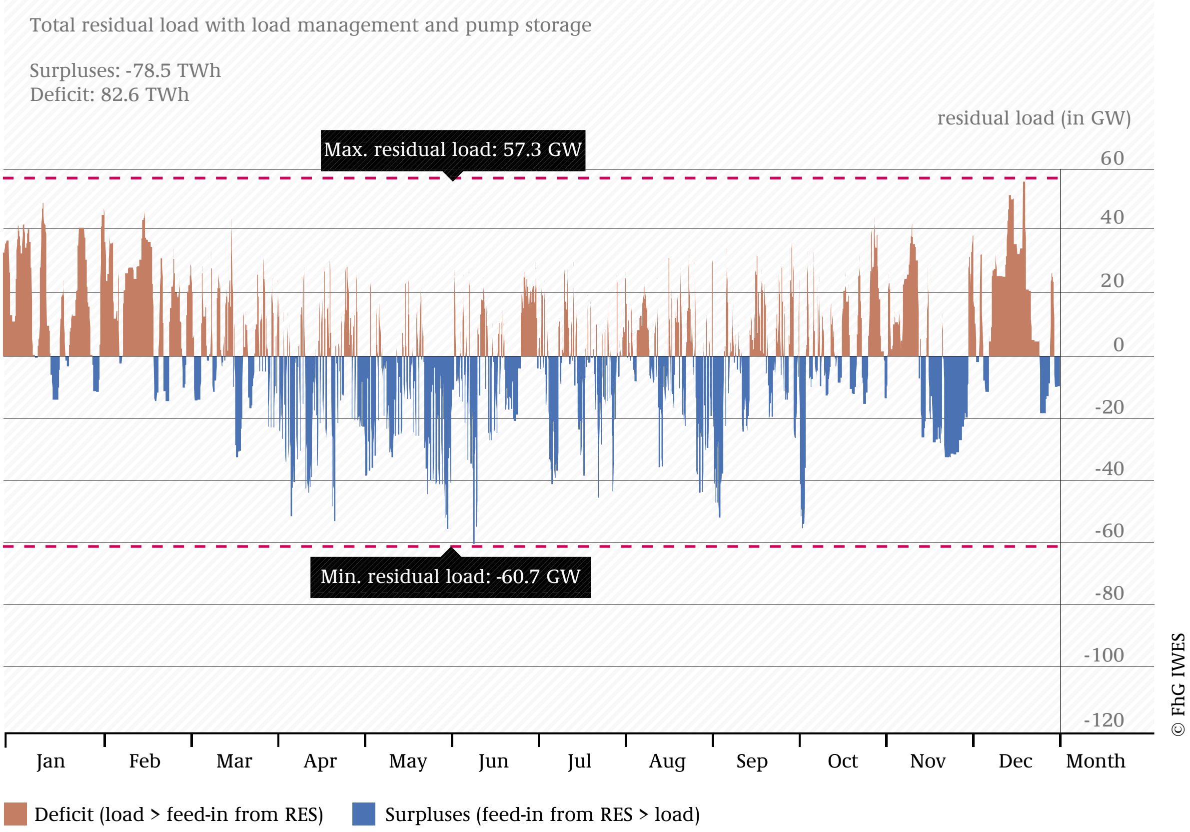
© FhG IWES

TOTAL RESIDUAL LOAD AND PUMP STORAGE CAPACITY

A further balancing option is short-term storage. Our simulation envisages that only pump storage power plants are used for this purpose.

As shown in Figure 7, load management and use of short-term storage flatten the residual load curve and decrease excess production compared to the residual basic load shown in Figure 5. Due to their limited capacity these options flatten the residual load curve only to a small degree.

FIGURE 7 TOTAL RESIDUAL LOAD WITH LOAD MANAGEMENT AND PUMP STORAGE IN THE YEAR 2050, BASED ON DATA FROM THE METEOROLOGICAL YEAR 2009



4.3 Long-term storage, electricity imports and reserve capacity

Both storage systems utilise electrolysis to handle excess power. To utilise 99% of the excess electricity, the installed electrolysis capacity does not need to match the maximum surplus generation of 69 GW; instead, 44 GW are sufficient.

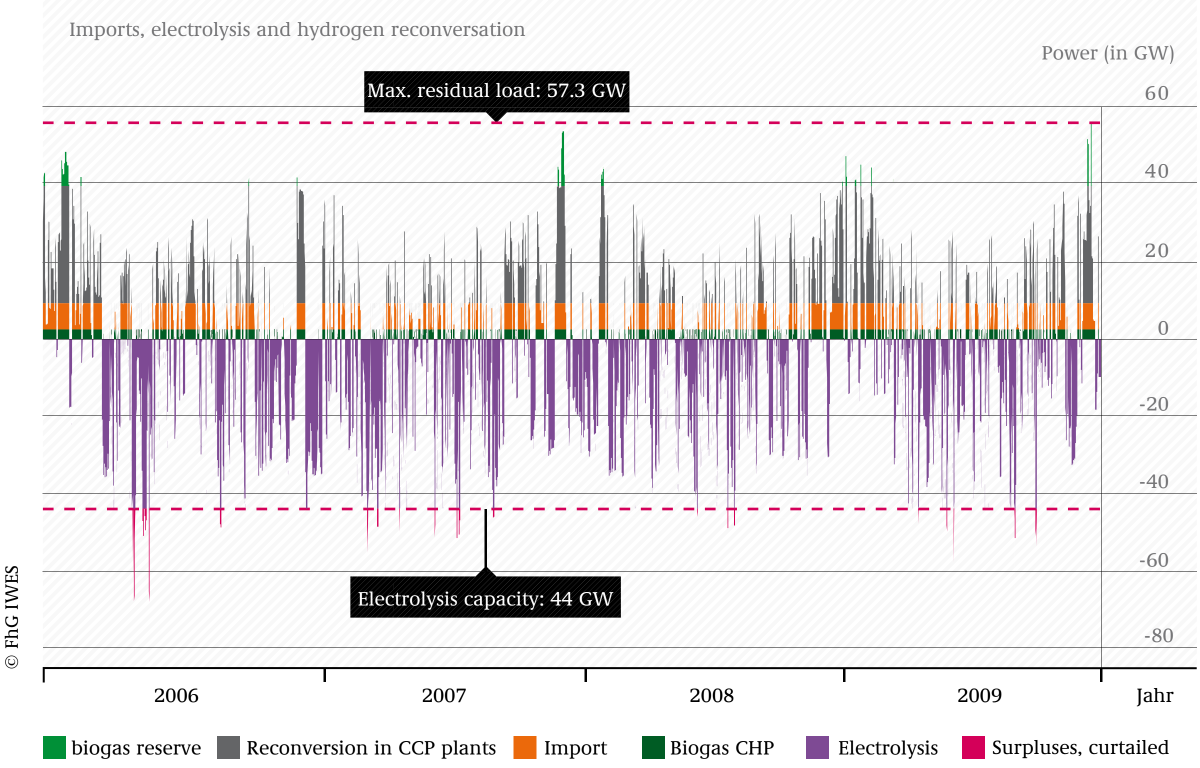
HYDROGEN STORAGE SYSTEM

To fully cover the load at any hour throughout the simulation period, the following gen-eration capacities were applied successively as needed:

(1) up to 2.5 GW CHP biomethane-gas turbines,
(2) 6.9 GW imports of electricity from renewable sources,
(3) 30.4 GW CCP plants for the reconversion of rp-hydrogen and
(4) 17.5 GW biomethane gas turbines without CHP as reserve capacity.

The use of electrolysers, hydrogen reconversion, biomethane conversion and imports for the entire simulation period are shown in Figure 8. The rp-hydrogen storage system has an efficiency of 42%.

FIGURE 8 USE OF ELECTROLYSIS, HYDROGEN RECONVERSION, BIOMETHANE GENERATION AND IMPORTS FOR THE SIMULATION PERIOD 2006-2009



© FhG IWES

Imports range from 19.7 TWh for the meteorological year 2007 to 26.5 TWh for 2006. The average across all four years is 23 TWh. This is slightly less than 5% of electricity consumption in 2050[22] and thus well below today's gross imports of 40 TWh. In these scenarios, imports are only used to even out the four-year energy balance. They are not necessary to ensure security of supply. Without these imports, renewable energy potentials would need to be exploited to a somewhat larger extent.

The hydrogen storage system requires cavern storage space volume of around 28 billion m^3. The constrained potential for storage in caverns in Germany is around 37 billion m^3, sufficient for 110 TWh_{th} hydrogen; consequently simultaneous natural gas and hydrogen storage is possible with existing storage capacity.

METHANE STORAGE SYSTEM

If the long-term storage system is run on rp-methane instead of rp-hydrogen, the total system efficiency decreases to 35% due to additional conversion losses.

Imports therefore slightly increase, on average to 30 TWh or around 6% of electricity consumption per annum.

The required storage volume of around 7.5 billion m^3 is therefore significantly lower than the constrained potential available in 2050.

4.4 Energy balances

Table 5 shows the results of power generation from renewable energy. Yearly generation varies between 514 and 555 TWh with a 4-year average of 534 TWh.

Table 6 and Figure 9 show the total energy balance for the meteorological years 2006-2009 as well as the average values for an rp-hydrogen storage system. The results for the rp-methane storage system differ only slightly from those for rp-hydrogen.

Since feed-in from renewable energy sources varies from year to year, so does electricity generation from reconversion of rp-hydrogen in CCP plants. Imports also vary from year to year.

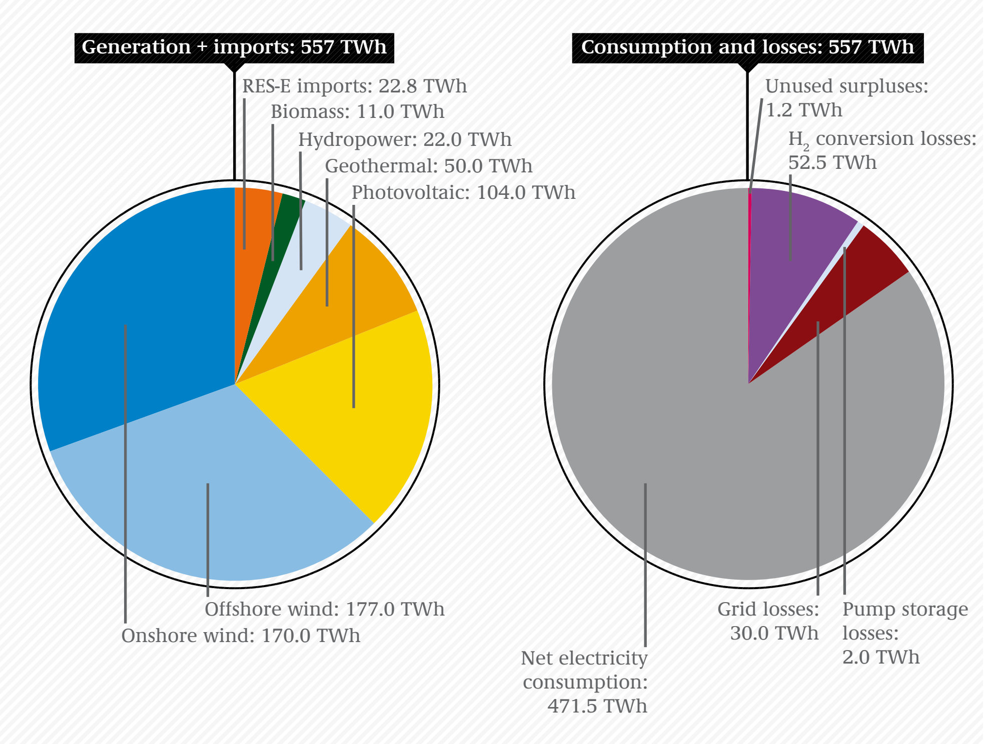
TABLE 5 ENERGY GENERATION, CAPACITY AND FULL-LOAD HOURS OF RES FOR THE METEOROLOGICAL YEARS 2006-2009

	2006	2007	2008	2009	Average
Geothermal: 6.4 GW					
Energy [TWh]	50	50	51	50	50
Full-load hours [h]	7884	7884	7906	7884	7889
Run-of-river power: 5.2 GW					
Energy [TWh]	22	23	23	21	22
Full-load hours [h]	4264	4502	4385	4001	4288
Wind onshore: 60 GW					
Energy [TWh]	163	184	174	158	170
Full-load hours [h]	2715	3071	2899	2634	2829
Wind offshore: 45 GW					
Energy [TWh]	171	183	185	168	177
Full-load hours [h]	3804	4065	4106	3741	3929
Photovoltaic: 120 GW					
Energy [TWh]	104	104	103	104	104
Full-load hours [h]	868	868	861	870	867
Biomass: 23.3 GW					
Energy [TWh]	13	10	9	12	11
Full-load hours [h]	546	435	393	516	472
Total renewable energy sources: 259.9 GW					
Energy [TWh]	**523**	**555**	**545**	**514**	**534**

TABLE 6 ENERGY BALANCE FOR THE LONG-TERM STORAGE SYSTEM "HYDROGEN" FOR THE METEOROLOGICAL YEARS 2006-2009

	2006	2007	2008	2009	Average
Generation					
Total RES (259.9 GW)	523.5	555.3	544.6	514.1	534.4
Pump storage (turbine)	5.8	5.9	6.1	6.1	6.0
Reconversion H_2	45.1	31.1	30.4	45.7	38.1
Imports	26.0	19.7	20.7	24.9	22.8
Demand					
Basic load	401.0	401.0	403.3	401.0	401.6
Air-conditioning	13	8.9	8.9	9.3	10.0
e-personal vehicles	50	50.0	50.0	50.0	50.0
Heat pumps	44	34.6	38.2	43.3	39.9
Pump storage (pump)	7.7	7.9	8.1	8.2	8.0
Electrolysis	84	108.3	92.8	77.4	90.5
Curtailment of excess supply	**1.8**	**1.4**	**0.4**	**1.2**	**1.2**

FIGURE 9 NET ELECTRICITY PRODUCTION WITHOUT STORAGE POWER PLANTS PLUS IMPORTS FROM RENEWABLE ENERGY SOURCES AS WELL AS NET ELECTRICITY CONSUMPTION AND LOSSES AS AVERAGE VALUES FOR THE METEOROLOGICAL YEARS 2006-2009 FOR THE GENERATION SYSTEM WITH HYDROGEN STORAGE



© FhG IWES

4.5 Security of Supply

The results of the simulation show that an electricity supply system based entirely on renewable energies can satisfy load requirements at any given hour of the year. Strictly speaking, these results could be the outcome of a lucky constellation of historic load and weather patterns in the four sample years. A stricter proof would be to demonstrate that the power generation system can satisfy the power requirement at any point in time even during extreme events with a pre-defined probability. The concept of guaranteed capacity provides such a proof. It factors in power plant failures and weather conditions with the probabilistic method of recursive convolution and the expectation on peak load.

With the installed capacity of wind power and photovoltaic increasing, the feed-in gradient, i.e. the change in feed-in from one moment to the next, increases as well. As a result, the total residual load will also see significantly higher gradients (i.e. faster changes) compared to today. These changes need to be balanced at any time by storage and reserve capacities.

Due to forecasting uncertainties for wind and photovoltaic energy, increases in installed capacity increase the need for balancing power, in other words the need for fast-response balancing capacity for unexpected deviations between generation and demand. Therefore it also needs to be shown that sufficient balancing power is available in the power system at all times to prevent outages.

Reserve power serves to balance power fluctuations in the time period of less than an hour. Since our simulation only allows for an hourly resolution, we separately assessed the provision of balancing power.

The results of the analysis show that in the Regions Network scenario power requirement could be covered at any moment at today's level of supply security[23].

Balancing of changes in load and RES-based generation as well as provision of balancing power can be guaranteed through a combination of load management, electricity storage and reserve power plants. With both electricity storage and reserve power plants, sufficient secured capacity is available at any time.

4.6 Conclusion

For Germany an electricity supply system based completely on renewable energies by 2050 is technically as well as ecologically feasible. Such a system can be implemented using currently available production and demand side technology and without compromising neither Germany's position as a highly industrialised country nor current lifestyles.

An electricity supply system based completely on renewable energies can – at any hour of the year – provide a security of supply on par with today's high standard. The results of our simulations show that renewable energies – through the interplay of production and load management and electricity storage – can meet the demand for electricity and provide the necessary control reserve at any time. This is possible even during extreme weather events as occurred in the four-year time period considered.

The constrained renewable energy potentials in Germany (considering technical and environmental constraints) were shown to be sufficient if – at the same time – available efficiency potentials in electricity consumption and building insulation are tapped.

The potentials identified in our simulation are also sufficient to cover the additional power demand from strongly increasing e-mobility and from the use of heat pumps to cover the entire heating and hot water demand, as well as for additional air conditioning.

The expansion of reserve power capacity, application of load management and the development of infrastructure for the transport and long-term storage of electricity are necessary prerequisites for a power system based solely on renewable energies in the year 2050.

Though this study has a purely national focus, it should be noted that the expansion of the European energy grid offers significant potential for increasing efficiency by balancing feed-in from wind and photovoltaic energy on a continental scale.

FOOTNOTES:

22 In 2009, Germany imported more than 40 TWh of electricity (gross import) while exporting 55 TWh over the same period.

23 In this study, we focussed on the interplay of generation and demand as well as the need for storage systems and load management. What types of grid technology solutions are needed to incorporate large shares of renewables should be analysed in further studies.

2050:
100 %
RENEWABLE ELECTRICITY

05

POLICY RECOMMENDATIONS

- Policymakers should agree on binding long-term mitigation targets for greenhouse gases for 2050 which, in the case of Germany, should be set along the upper end of the 80-95% trajectory recommended by the IPCC. The restructuring of the energy system requires a clear trajectory for the rate of expansion of renewable energies with binding long-term targets.

- Efficient and intelligent utilisation of energy is the key. Without a reduction of present energy consumption levels, particularly in the space heating sector, a 100% renewable energy supply will be difficult to achieve. Therefore, among other instruments, the EU Ecodesign Directive should be strengthened; energy management in commerce and industry should be compulsory and energy efficiency requirements for buildings need to be tightened. In addition, highest possible energy efficiency must be achieved in the transport sector. As our simulation has shown, dispatchable loads are a key element in a renewable energy system. Load management potentials must be tapped using suitable instruments such as economic incentives.

- Policymakers should aim at tightening the ETS, reducing environmentally harmful subsidies as well as passing an ecological tax reform. Finally, German policymakers should consolidate German climate protection legislation into a single climate act, strengthen the role of local authorities and develop new market structures adapted to the characteristics of renewable energy sources.

- Spatial planning needs to be adapted to facilitate the establishment of wind power plants and clarify the situation of underground planning.

- The restructuring of the energy system requires major infrastructural projects to optimise and expand electricity grids and develop energy storage facilities and transport systems.

- Expansion and optimisation of the transmission and distribution grid, though not addressed in great detail in this study, is of utmost importance to enable the increase of renewable energy generation.

- During the transition period the energy sector will require highly flexible gas-fired power plants, as well as efficient gas CHP power plants. As has been shown by UBA[24], additional construction of coal-fired power plants will not be necessary to secure energy supply.

- Renewable energy production, though in general more environmentally friendly than conventional power production, is not without negative environmental impacts. For example, increasing the share of renewables requires the expansion of transmission grids and storage facilities, leading to resource consumption, land sealing, etc.. Any technology replacing conventional power production will need to meet sustainability criteria going beyond climate change mitigation aspects. To name a few examples, renewable energy technology needs to be efficient in its use of non-renewable resources and must meet health and safety requirements.

- Any transition process will require the necessary experts and technologies. R&D in the energy sector and adjustment of the education system are prerequisites to put a 100% renewable energy system on the ground.

- Lastly, but highly important, social support for the transition process must be generated by making it a democratic, participatory process.

It must be clear that a complete transition of the electricity sector presents a great challenge but needs to start today to avoid the most severe impacts of climate change.

FOOTNOTES:

24 UBA (2009)

REFERENCES

BMU 2008
Nitsch, J. (2008): Leitstudie 2008 – Weiterentwicklung der Ausbaustrategie Erneuerbare Energien vor dem Hintergrund der aktuellen Klimaschutzziele Deutschlands und Europas. Studie im Auftrag des Bundesumweltministeriums, Berlin, Stuttgart

BMU 2009a
Nitsch, J. & Wenzel, B. (2009): Leitszenario 2009 – Langfristszenarien und Strategien für den Ausbau Erneuerbarer Energien in Deutschland. Studie im Auftrag des Bundesumweltminister iums,Berlin, Stuttgart, Teltow

BMU 2010
Nitsch et al. (2010): Leitstudie 2010 - Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global. Studie im Auftrag des Bundesumweltministeriums, Berlin.

Brinner 2002
Brinner, A. & Hug, W. (2002): Dezentrale Herstellung von Wasserstoff durch Elektrolyse. „http://www.dlr.de“www.dlr.de

DENA 2008a
Deutsche Energie-Agentur (2008): Untersuchung der elektrizitätswirtschaftlichen und energiepolitischen Auswirkungen der Erhebung von Netznutzungsentgelten für den Speicherstrombezug von Pumpspeicherwerken. Studie im Auftrag von Vattenfall Europe Transmission; Berlin

Enquete-Kommission 2002
Enquete-Kommission „Nachhaltige Energieversorgung unter den Bedingungen der Globalisierung und der Liberalisierung“ (2002): Endbericht. Drucksache: 14/9400, 07.07.2002, Deutscher Bundestag 14. Wahlperiode, Berlin

DLR/FEU/WI 2004
Deutsches Zentrum für Luft- und Raumfahrt, Institut für Energie- und Umweltforschung & Wuppertal Institut für Klima, Umwelt und Energie (2004): Ökologisch optimierter Ausbau der Nutzung erneuerbarer Energien in Deutschland. Forschungsvorhaben im Auftrag des Bundesumweltministeriums; Stuttgart, Heidelberg, Wuppertal

FFE 2009c
Forschungsstelle für Energiewirtschaft e.V. & Institut für Wirtschaftsforschung (IFO) (2009): Energiezukunft 2050. Studie im Auftrag von EnBW, E.ON Energie, RWE Power, Vattenfall Europe; München

FVS 2004
ForschungsVerbund Sonnenenergie (2004): Wasserstoff und Brennstoffzellen – Energieforschung im Verbund. In: FVS Themen 2004, Berlin „http://www.fvee.de/fileadmin/publikationen/Themenhefte/th2004/th2004.pdf“http://www.fvee.de/fileadmin/publikationen/Themenhefte/th2004/th2004.pdf

GE 2009
GE Energy (2009): Heavy duty gas turbine products. „http://www.gepower.com“http://www.gepower.com

Greenpeace 2009
EUtech (2009): Klimaschutz: Plan B – Energiekonzept für Deutschland. Studie im Auftrag von Greenpeace, Hamburg

Kleinmaier 2010
Kleimaier, M. (2010): Wasserstoff – Eine Option für die langfristige Speicherung von Windenergie (Ergebnisse einer VDE-Studie). DWV Pressekonferenz, 18. Februar 2010, Berlin HYPERLINK „http://www.h2de.net/aktuelles/Pressemeldungen/2010/pm1001_vde.pdf“http://www.h2de.net/aktuelles/Pressemeldungen/2010/pm1001_vde.pdf

Saint-Drenan et al. 2009
Saint-Drenan, Y.M.; Bofinger, S.; Gerhard, N.; Sterner, M. & Rohrig, K. (2009): Summenganglinien für Energie 2.0. Abschlussbericht, Institut für Solar Energieversorgungstechnik und Bundestagsfraktion Die Grünen. Berlin, Kassel

Schulz 2009
Schulz, D. (2009): Speicherpotenziale von Pumpspeicherwerken in Tagebaurestlöchern ehemaliger Braunkohlereviere. Forum Netzintegration, Deutsche Umwelthilfe, 30.09.2009, Berlin

SRU 2010
Sachverständigenrat für Umweltfragen (2010): 100 % erneuerbare Stromversorgung bis 2050: klimaverträgliche, sicher, bezahlbar. Stellungnahme Nr. 15, Mai 2010, Berlin

Stern 2007
Stern, N. (2007): The Economics of Climate Change - The Stern Review. University Press, Cambridge

Sterner 2009
Sterner, M. (2009): Bioenergy and renewable power methane in integrated 100 % renewable energy systems. Dissertation, Universität Kassel

Sterner et al. 2010
Sterner, M.; Gerhardt, N.; Saint-Drenan, Y.-M.; Oehsen, A. von; Hochloff, P.; Kocmajewski, M.; Jentsch, M.; Lichtner, P.; Pape, C.; Bofinger, S. & Rohrig, K. (2010): Energiewirtschaftliche Bewertung von Pumpspeicherwerken und anderen Speichern im zukünftigen Stromversorgungssystem. Studie im Auftrag der Schluchseewerk AG, Fraunhofer IWES, Kassel

UBA 2002
Wuppertal Institut für Klima, Umwelt, Energie & Deutschen Zentrum für Luft- und Raumfahrt (2002): Langfristszenarien für eine nachhaltige Energienutzung in Deutschland. Climate Change 02/2002, Studie im Auftrag des Umweltbundesamtes, Dessau

UBA 2009
UBA (2009) Climate Change Mitigation with a Secure Energy System. Developing a Sustainable Power Supply. Climate Change 13/09

UBA 2010b
Schleich, J.; Duscha, V. & Peterson, E. B. (2010): Environmental and economic effects of the Copenhagen pledges and more ambitious emission reduction targets. Zwischenbericht, Studie im Auftrag des Umweltbundesamt, Dessau-Roßlau. In Vorbereitung

UBA 2010c
Umweltbundesamt (2010): Berichterstattung 2009 unter der Klimarahmenkonvention der Vereinten Nationen. „http://www.umweltbundesamt.de/emissionen/publikationen.htm“ http://www.umweltbundesamt.de/emissionen/publikationen.htm

UBA 2010
UBA (2010): Energieziel 2050 – 100% Strom aus erneuerbaren Quellen, Dessau-Roßlau

WWF 2009
Öko-Institut; Prognos & Ziesing, H.-J. (2009): Modell Deutschland – Klimaschutz bis 2050: Vom Ziel her denken. Studie im Auftrag des WWF, Berlin

ZSW/IWES/Solar Fuel 2009
Zentrum für Sonnenenergie- und Wasserstoffforschung Baden-Württemberg; Fraunhofer Institut für Windenergie und Energiesystemtechnik & Solar Fuel Technology (2009): Speicherung von Bioenergie und erneuerbarem Strom im Erdgasnetz. In: FVEE & AEE (Hrsg.), Themen 2009 – Forschen für globale Märkte erneuerbarer Energien (S. 69-78), Berlin

ABBREVIATIONS

CCPP	combined cycle power plant
CCP plant	combined cycle power plant
CHP	Combined heat and power
GDP	Gross domestic product
GHG	greenhouse gases
GW	Gigawatt
HVDC	High-voltage, direct current
IPCC	Intergovernmental Panel on Climate Change
MW	Megawatt
IWES	Fraunhofer Institute for Wind Energy and Energy System Technology
ORC	Organic Rankine Cycle
R&D	Research and development
RES	Renewable energy sources
RES-E	Renewable energy sources - Electricity
rp-hydrogen	Renewable power hydrogen
rp-methane	Renewable power methane
SNG	Substitute Natural Gas
TWh	terawatt hour
UBA	Federal Environment Agency Germany
ZSW	Centre for Solar Energy and Hydrogen Research Baden-Württemberg

IMPRINT

Published by:
Federal Environment Agency Germany

Umweltbundesamt
Wörlitzer Platz 1, 06844 Dessau-Roßlau
Germany

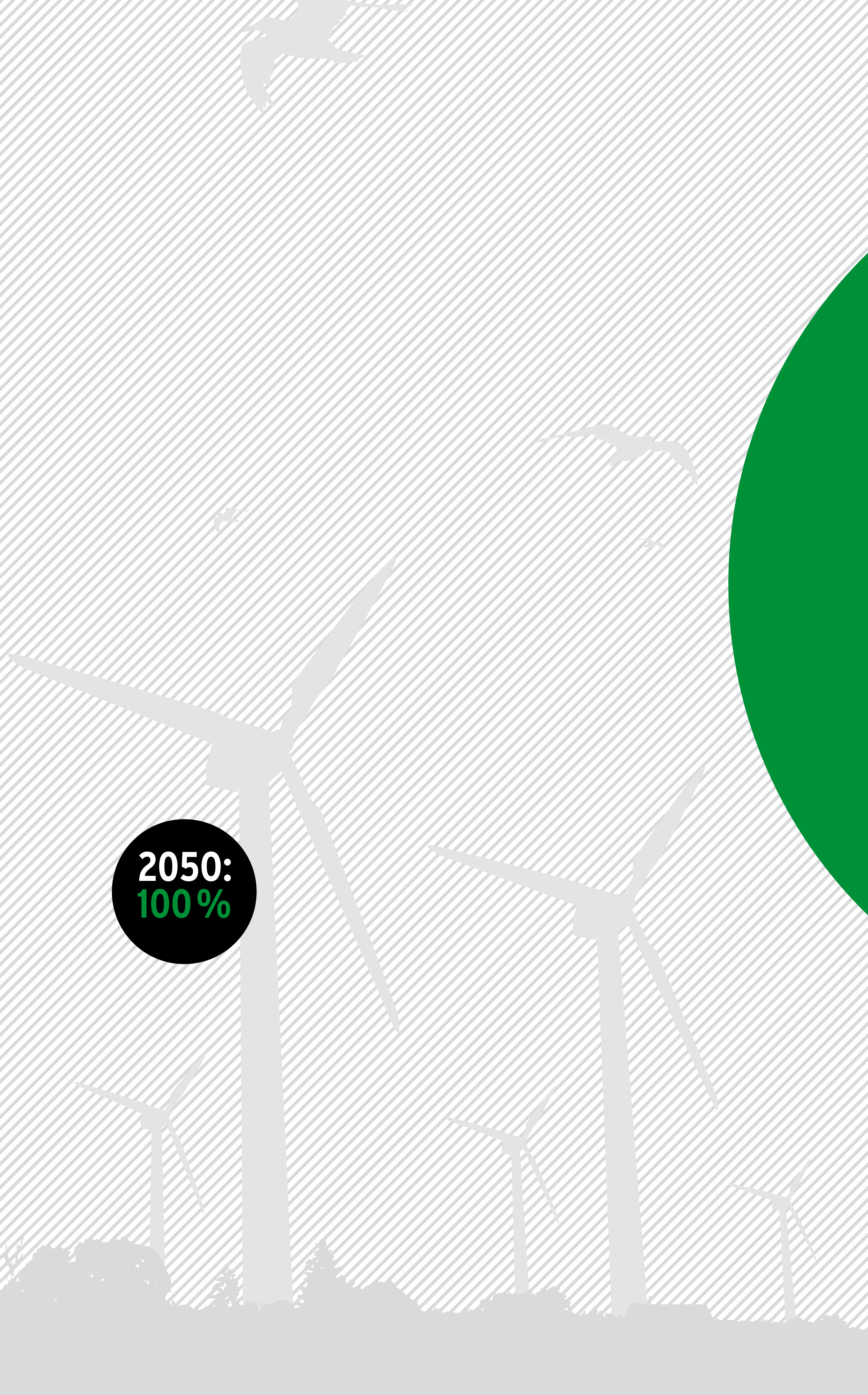
Phone: +49 340 / 2103 - 0
E-Mail: info@umweltbundesamt.de
Internet: www.umweltbundesamt.de
www.fuer-mensch-und-umwelt.de

Translation:
Sarah Rieseberg

Design:
Studio GOOD, Berlin
www.studio-good.de

Printed on recycled paper awarded the Blue Angel eco-label

This publication is part of the public information
activities of the Federal Environment Agency.
It can be obtained free of charge at:
GVP | Postfach 30 03 61 | 53183 Bonn | Germany
Service phone: +49 340/2103 - 6688
Service fax: +49 340/2103 - 6688
Email: uba@broschuerenversand.de



2050:
100 %